



Design of a Floating Curved Photovoltaic Panel with IoT-Enabled Weather Monitoring for Rivers and Lakes Environments

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Abstract

Floating photovoltaic (PV) systems enable solar energy generation on water bodies, alleviating land scarcity whilst providing potential cooling and reflection benefits that enhance panel performance. However, many floating installations employ flat PV modules without optical concentration or integrated tracking, which limits their energy yield in tropical environments such as rivers and lakes. This study designs a floating solar platform that incorporates a curved PV configuration mounted on a buoyant platform, a single-axis sun-tracking mechanism and an IoT-based weather and performance monitoring system designed for riverine deployment. This prototype employs an 18 V, 250 W monocrystalline flexible solar panel formed into a curved trough that is controlled by an Arduino-based tracking system and a NodeMCU-based monitoring subsystem to record voltage, temperature and humidity via a mobile application. Experimental testing on the Damansara River indicates that the floating curved system achieves a maximum power output of 231 ± 5 W, which is higher compared with the output of a flat-land-based configuration (190 ± 7), corresponding to an efficiency enhancement of approximately 21% at a solar radiation intensity of 1200 W/m^2 . The floating configuration also exhibits reduced efficiency degradation with increasing ambient temperature due to the cooling effect of the water body and elevated humidity, which together mitigate thermally induced performance losses. These findings demonstrate that the proposed curved floating solar platform provides a feasible and environmentally friendly solution for increasing PV energy yield whilst conserving land resources in tropical regions.

Keywords: Curved solar; Floating platform; Sun tracker; Solar; Solar monitoring system

1. Introduction

The significant consumption of global energy resources in recent years has prompted governments, industry players and academic groups to search for new energy sources and achieve greater energy efficiency. Given that land covers only about 29% of the Earth's total surface area [1], the installation of solar power plants, which often require a large space, is often constrained by the lack of available land [2],[3]. Therefore, installing large-scale solar power plants may not be feasible in countries with crowded cities and limited farmland. To address this limitation, floating solar

platforms with a curved solar system have been introduced as an alternative. These platforms involve the installation of solar panels on buoyant platforms atop bodies of water, such as lakes, rivers, oceans and hydropower reservoirs [4]. Supported by a high-density polyethylene (HDPE) raft with corrosion-resistant piping, geomembranes and plastic lumber [5], this floating mechanism keeps the solar system undamaged.

A solar tracking system can optimise the capacity of solar arrays to convert solar energy into usable electricity by adjusting the panels' orientation throughout the day to follow the sun's optimal angle of incidence. Solar trackers offer

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significant benefits for expansive, autonomous solar installations, including solar trees and ground-mounted solar panels. This mechanism enables solar panels to continue monitoring the sun and maintain their efficiency even when the raft experiences water flow caused by its inclination or rotation [6]. The efficiency of solar panels in converting sunlight into electricity depends on the angle at which the sun's rays strike these panels' surface; thus, their energy conversion efficiency increases as the angle of incidence decreases [7]. Solar trackers can reduce this slant by adjusting the panels to align them with the sunlight [8]. An east-west-aligned single-axis tracker has also been incorporated into this system to facilitate panel rotation and to optimise the collection of sunlight [9]. Apart from tracking the sun's daily movement, this system may also record seasonal changes in its altitude [10], [11].

In the past, only a few scholars have investigated the installation and use of solar devices in the rural areas of developing countries. For instance, S. Tibebu and A. Hailu [12] designed, built and assessed the performance of parabolic solar cookers and compared them with firewood, charcoal, kerosene and electricity based on their cooking time and energy costs. Results show that compared with these fuels, the constructed parabolic solar cookers managed to cook Nefro and Shero within the shortest time, but these cookers were outpaced by firewood and charcoal in boiling water. Kumar et al. [13] designed a novel solar food steamer based on a parabolic dish concentrator for domestic food preparation and found that the system achieved its highest energetic and exergetic efficiencies for sweet potato at 72.83% and 15.14%, respectively.

Since the publication of these studies, much progress has been achieved in improving solar collectors [14-19]. Concentrated solar energy is an economical and evolving technology in the renewable energy sector. However, this technology faces a challenge in maintaining heat generation after the collection of sunlight, with heat storage in oil or salt being less costly than battery energy storage [20]. This study thus focuses on the three-fold overall theoretical maximum for the acceptance angle across four optical concentrative technologies [21], [22], namely, parabolic troughs, concentrated platters, Fresnel linear reflectors and solar energy towers, which show promising application in rural areas due to their comfortable and clean environment.

Mason and Reitze built low-cost parabolic trough solar collectors [23] with the same opening width, collector length and region measurements. The absorber tubing was made of copper, and the

heat-transfer fluid was conveyed by water. To minimise heat losses, these collectors were designed using solar concentrators with a 128 ratio. Umair et al. [24] designed a parabolic concentrator with wings oriented towards the east and west directions (surface Azimuth angle). They evaluated the efficiency of this concentrator at tilt angles ranging from 70° to 90° with the main goal of determining the maximum operating temperature of a solar concentrator system.

The present study aims to create a floating curved solar system that leverages curved light-focusing principles to significantly enhance its energy generation effectiveness. This system increases total electricity production by using the sun-following mechanism to improve the light angle. This study offers two key contributions. First, this study presents a floating solar platform design that combines a bent solar collector with a 1D tracking system on a buoyant base specifically designed for river conditions. Second, this study uses an IoT-connected monitoring system to collect real-time environmental and performance data, including sunlight levels, temperature, humidity and power output.

2. State of the Art

Large-scale solar energy installations have become critical to address the rising global demand for power, the rapid depletion of fossil fuel sources and the growing concerns about environmental protection. However, only a limited amount of land is available for the installation of solar power systems. As an alternative, these installations can be placed over water surfaces, including large lakes, oceans, small lagoons, irrigation ponds, reservoirs, wastewater treatment plants, vineyards, aquaculture facilities, dams and navigational channels, to help conserve land and water resources [25] as shown in Figure 1a. These floating-type solar PV panels, as shown in Figure 1b, offer several advantages over land-based panels, including fewer obstructions to sunlight, greater convenience and improved energy and power generation efficiency as temperatures under the panels tend to be cooler. Additionally, the shading provided by these panels can benefit water bodies by reducing evaporation, limiting algae growth and improving water quality to some extent [26].

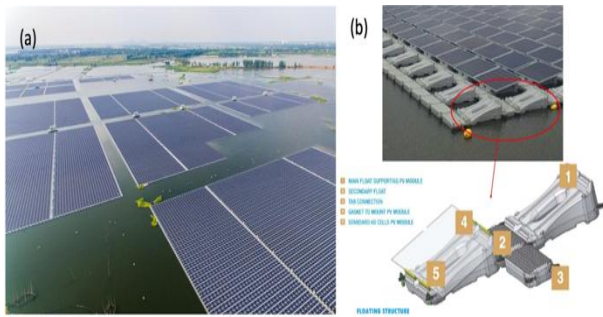


Fig. 1. (a) Floating solar power plants [25], and (b) floating solar technology design [26].

To meet surging energy demand and reduce the impacts associated with declining land and water availability for electricity generation, floating solar photovoltaic (FPV) systems, also known as floating solar panels, have gained traction across the electricity industry, including in Asia. More than 80% of installed FPV projects in the world are located in the Asia-Pacific region, with China, Japan and Korea being the largest contributors [27]. Experts predict that FPV will continue to proliferate globally and potentially account for 1.9% (or 710 TWh) of the global electric output by 2030 [28].

FPV is strategically advantageous compared to traditional solar panels, which are either ground or roof mounted. When combined with hydropower facility components, FPV may provide a variety of synergistic advantages. For instance, FPV can utilise existing transmission systems for installation, reduce energy waste during periods of low demand, improve power quality from PVs, reduce the amount of basin water needed to produce power and lessen erosion on hydropower facility reservoirs due to wave activity caused by wind, storms and flooding [28-30]. Sanchez et al. [31] and Lee et al. [30] (Figure 2) found that only 1% of existing hydropower facility reservoirs in Africa have been outfitted with FPV, yet approximately 53

TWh of electric power remains available in the region to meet 72% of the increased electric power needs projected by 2040.

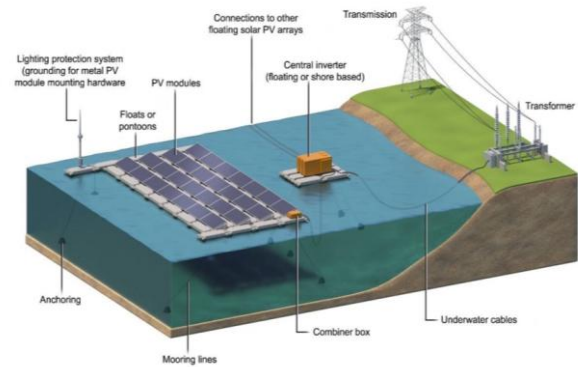


Fig. 2. Floating PV system [30].

This study reviews the literature on floating solar panels and their installation by retrieving relevant articles on Scopus on July 20, 2025 using the keywords 'floating and solar panels'. Figure 3(a-d) present the related statistics.

Several studies have investigated the environmental impacts of floating solar panels, specifically on water quality and aquatic ecosystems. Research in Korea found that floating solar panels have no substantial impact on water quality or aquatic ecosystems [34], whilst another study in China found that floating solar panels have no significant impact on water quality or phytoplankton biomass [35]. Whilst some studies have underscored the absence of environmental impacts of floating solar panels, other scholars have highlighted the roles of FPV in outcompeting habitats and in the migration of aquatic species [36, 37].

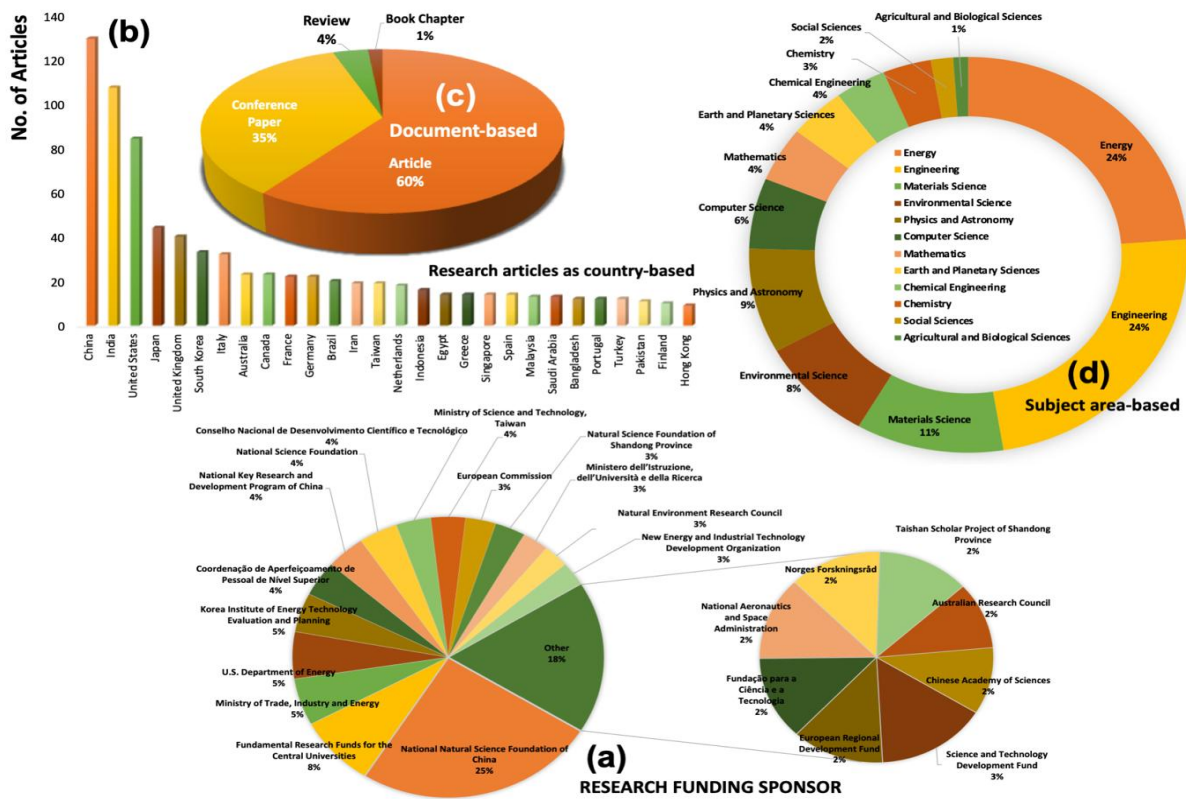


Fig. 3. Scopus database analysis using the keywords ‘floating + solar panels’ accessed on July 20, 2025, focusing on (a) sponsor-funded, (b) country-based, (c) document-based and (d) subject-area-based research.

Various studies have compared the energy efficiency of FPV systems with that of land-based PV systems. Tina et al. [38] found that FPV systems may produce an energy surplus of 3.4%–7.3% compared with on-ground systems. Choi et al. [39] confirmed that FPV systems produce about 10% more energy than ground-based PV systems with a temperature difference of about 3.5 °C. Liu et al. and Dörenkämper [40], [41] supported this finding by revealing that FPV systems achieve a 6% increase in energy yield in Singapore and a 3% increase in the Netherlands. Santafé [42] evaluated an FPV system on irrigation reservoirs, which yielded 425,000 kWh of electricity and saved an estimated 5,000 m³ of water annually. Renewable energy demand led Choo et al. [43] to examine the growth of solar energy, which encompasses a range of technologies, including solar thermopower, dye-sensitised solar cells, PV concentrated cells and solar-based power.

Solar PV installations require a large amount of land, which in itself is expensive. However, these costs can be reduced by leveraging the abundance of water bodies [44], [45]. Although solar energy is a renewable source, its efficiency can fall below 15% throughout its lifetime [46]. In addition, given that water is a natural heat sink, the power generated

from FPV is often greater than the power generated from ground-mounted and rooftop systems. High-density polyethylene (HDPE), which is used to fabricate floating platforms, is also resistant to ultraviolet light and corrosion. These ‘floating offshore solar fields’ or ‘solar islands’ may be categorised as ‘very large floating structures’ (VLFS) [47]. These structures must comply with the extant strength and safety standards and, at a minimum, meet the operational conditions necessary for their operation [48].

A VLFS is defined as a manufactured landmass floating on water. Two standard types of VLFS are available, namely, semisubmersible and pontoon VLFS [49, 50]. Column tubes or ballast structural elements are used to elevate these platforms above sea level, allowing their installation in high-seas areas with large waves. Examples of VLFSs include (i) the Mega-Float, which is a floating airport in Tokyo Bay; (ii) a floating island on the Han River; (iii) a floating performance stage in Marina Bay, Singapore; and (iv) a floating oil storage facility on Kamigoto Island [51]. Mohd Alif Saifuddin Jamalludin et al., investigated the potential implementation of floating solar technologies in the coastal or infield areas of Malaysia as shown in Figures 4a and 4b [52].

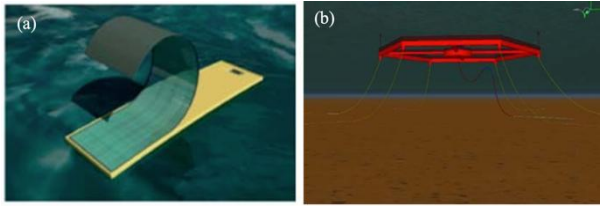


Fig. 4. (a) PV panel array affixed to a buoyant floating platform, and (b) 3D view – hexagonal shape [52].

FPVs offer many countries the valuable opportunity to generate their own power. This

research estimates that if six systems are strategically installed in selected land and water areas across Malaysia, then they will produce about 14,530 MWh of renewable energy per year [53]. This study then evaluates whether this type of asset can be developed as a broad-scale system with minimal maintenance requirements. The economic viability of the floating solar cells design must also be considered. Table 1 presents key studies on floating solar stills and highlights their significant findings.

Table 1,
Overview of pertinent research on floating solar panels.

Authors	Location	Evaluation approach	Installation type/model	Environmental impact	Maintenance
Kumar Agrawal et al. [54], 2022	Uttar Pradesh, India	Experimental and simulation	Anchoring and mooring systems	–	Reduces water evaporation; conserves agricultural land; \$0.011/W _p operations and maintenance cost
M. Lopez et al. [55], 2022	Spain	Experimental	Rigid FPV systems with crystalline silicon modules	–	~80 TWh/year electricity; reduces GHG by 27%; 3.4 €/kW annually
Ramanan C.J. et al. [56], 2024	Not specified	Simulation	A single solar PV panel	Not specified	Not specified
Seok Min Choi et al. [57], 2022	Republic of Korea	Experimental and simulation	Different sizes of PV systems	Not specified	Reduces manufacturing costs of floating PV systems
Giles Exley et al. [58], 2022	Estimated UK reservoirs	Simulation	MyLake model with enhanced phytoplankton biomass	Impact on aquatic ecosystem depends on siting of FPV array	Not specified
Emerson L. Alberti et al. [59], 2023	Santa Clara hydroelectric power plant reservoir, Southern Brazil	Experimental	Anchorage and mooring designs	Water cooling offers higher efficiency but poses challenges for aquatic ecosystems	Regular inspections and repairs
Andrea Mignone et al. [60], 2021	Santa Clara hydroelectric power plant reservoir, Southern Brazil	Simulation	Gable structure	Floating PVs pose risk to aquatic ecosystems due to shading, which affects algal growth, fish and plants	Not specified
Abu Kowsar et al. [61], 2023	Hakaluki Marshland, Bangladesh	Experimental and simulation	Monocrystalline 550 W solar panel (LR5-72HPH 550M)	The floating solar PV plant has lower CO ₂ emissions than a pole-mounted power plant	High maintenance rate due to imported materials
Z. A. A. Majid et al. [62], 2014	Pahang, Malaysia	Simulation	80 W multicrystalline model (Sharp NE80E2EA)	Environmentally friendly technology	Not specified
D R Aryani et al. [63], 2019	Jawa Barat, Indonesia	Experimental	50-W _p PV module	Reduces water evaporation and prevents algae by casting shadows from the panels	Not specified

A comprehensive study of floating solar platform technology as an alternative renewable energy solution requires an extensive comparative analysis of the multiple ways of collecting solar energy. This comparison provides a basis for establishing a floating solar platform as a viable renewable energy technology. A comparative analysis of various renewable energy technologies will also assist researchers and end users in evaluating how the floating solar platform can generate sustainable energy. Figure 5 presents a comprehensive comparative analysis of renewable energy solutions proposed in the literature.

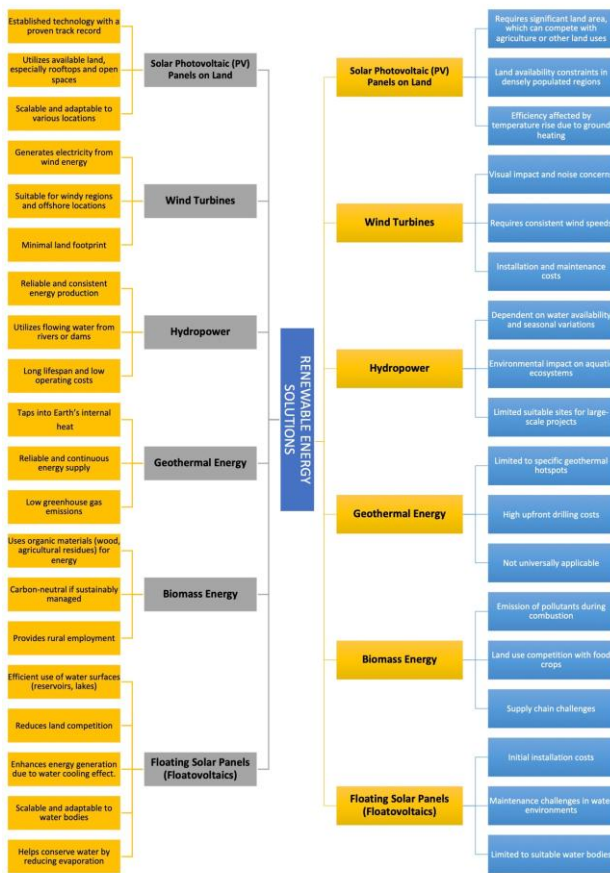


Fig. 5. A comprehensive comparative analysis of the advantages and disadvantages of various renewable energy solutions.

3. Methodology

3.1. Project Methodology

The curved solar platform was constructed by following the system development life cycle methodology that involves five stages, namely, requirement analysis, design, development and coding, testing and project maintenance. Each stage is considered separate and is not repeated.

3.1.1. Requirement Analysis

The floating solar platform, with its explicitly indicated parabolic-shaped solar system, was envisioned at this stage. The fact-finding process established the current methods along with their limitations and requirements. An issue statement for the floating solar platform with a parabolic solar-shape system was also formulated to ensure the creation of a clean, environmentally friendly system that does not require fuel or real estate. Findings suggest that accumulation is the root cause of nano-fluid instability. Typically, the use of appropriate surfactants is required to address these stability issues.

3.1.2. Design

The conceptual design of the floating solar platform was created at this stage in consideration of various parameters and requirements. Using SOLIDWORKS, the physical structure of the platform was developed until the conceptual design justifies the purpose and scope of the project. The physical design efficiently manages product data, automates workflows and generates real-time solar system designs. Single-axis tracking prototypes were embedded to track the sun in the vertical and horizontal planes (elevation and azimuth) to maximise light intensity. The solar panel can be tilted left and right along the azimuthal axis.

The primary aim of the floating platform design is to ensure that the structure remains buoyant even in adverse weather conditions. Advanced designs have been combined with adjustable buoyancy systems to quickly adapt to changes in water conditions. During the design phase, experiments and simulations were conducted to better understand the environmental challenges faced by these floating solar panels. The anchor system consists of submerged piles, gravity anchors and new technologies, including suction cups, that were chosen in consideration of the specific water body characteristics and environmental conditions at the intended implementation site.

3.1.3. Implementation

The implementation stage evaluated whether all components of the floating solar platform were designed in accordance with its physical design, the circuit diagram and the specifications of the project. The installation of floating solar panels may face significant ethical issues arising from privacy violations and the collection of surveillance data. These ethical standards underscore the importance

of protecting the integrity of data collection and receiving community support for the project. Therefore, promoting public awareness and developing the relevant regulations and frameworks are both critical to effective monitoring.

3.1.4. Maintenance

After the maximum voltage output and safety of the prototype were established, potential hardware or software bugs were corrected to ensure the constant functioning of the floating solar platform.

3.2. Development Methodology

The single-axis tracking system for the floating platform was created in four segments using a parabolic solar system. In the first segment, an input source was created for the solar system, which comprises a light-dependent resistor (LDR) module. The processor was developed in the second segment. Arduino Uno and NodeMCU ESP8266 controllers were used to control the speed and output of the system, respectively. The third segment focused on the solar system outputs, including the H-bridge operation as a linear actuator, DC motor control and speed optimisation.

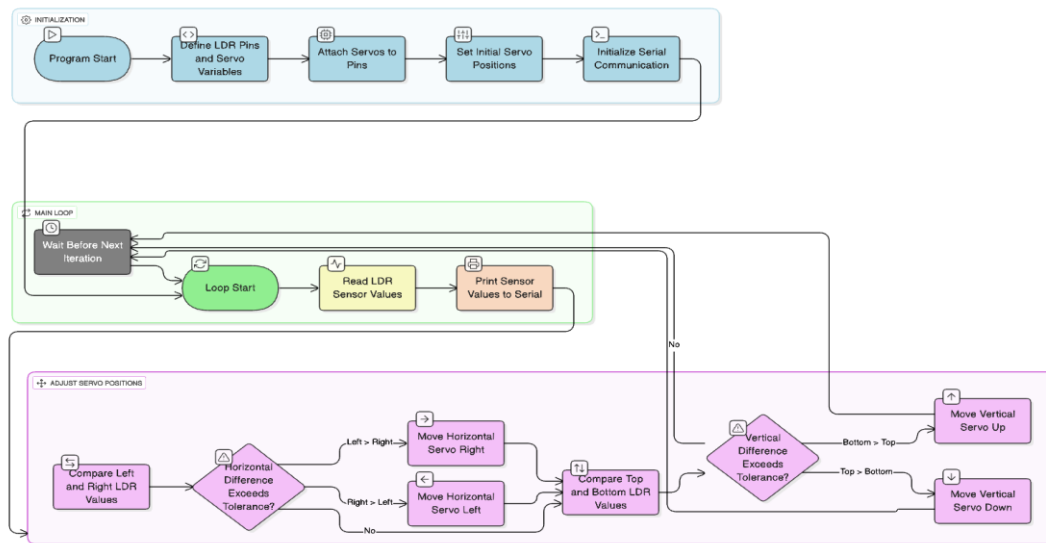


Fig. 6. Flowchart of the algorithm logic functionality.

The solar tracking system algorithm (Fig. 6), which includes a pseudo-code that can be translated into an Arduino code, is presented as follows:

Step 1: Initialisation

```
#include <Servo.h>
// Define LDR pins
const int LDR_Top = A0;
const int LDR_Bottom = A1;
const int LDR_Left = A2;
const int LDR_Right = A3;
// Define Servo objects
Servo servoHorizontal; // For left-right
movement
Servo servoVertical; // For up-down movement
// Define initial positions for the servos
int posHorizontal = 90; // 0° to 180°, starting at
middle
int posVertical = 90; // 0° to 180°, starting at
middle
void setup() {
// Attach servos to corresponding pins
```

```
servoHorizontal.attach(9); // Example pin
servoVertical.attach(10); // Example pin
// Set initial positions
servoHorizontal.write(posHorizontal);
servoVertical.write(posVertical);
```

```
// Initialize Serial Monitor
Serial.begin(9600);
}
```

Step 2: Read the analogue values from the LDRs

```
void readSensors(int &top, int &bottom, int
&left, int &right) {
top = analogRead(LDR_Top);
bottom = analogRead(LDR_Bottom);
left = analogRead(LDR_Left);
right = analogRead(LDR_Right);
}
```

Step 3: Compare the values from the LDRs to determine the direction of movement

```
void adjustPosition(int top, int bottom, int left, int
right) {
```

```

// Define tolerance to prevent constant small
movements
int tolerance = 50;
// Horizontal movement (left-right)
if (abs(left - right) > tolerance) {
  if (left > right) {
    posHorizontal += 1; // Move right
    if (posHorizontal > 180) posHorizontal =
180; // Limit to 180°
  } else {
    posHorizontal -= 1; // Move left
    if (posHorizontal < 0) posHorizontal = 0; //
Limit to 0°
  }
  servoHorizontal.write(posHorizontal);
}
// Vertical movement (up-down)
if (abs(top - bottom) > tolerance) {
  if (top > bottom) {
    posVertical -= 1; // Move down
    if (posVertical < 0) posVertical = 0; // Limit
to 0°
  } else {
    posVertical += 1; // Move up
    if (posVertical > 180) posVertical = 180; //
Limit to 180°
  }
  servoVertical.write(posVertical);
}
}
}
Step 4: Main loop
void loop() {
  int top, bottom, left, right;
  // Read the sensor values
  readSensors(top, bottom, left, right);
  // Print the sensor values for debugging
  Serial.print("Top: "); Serial.print(top);
  Serial.print(" Bottom: "); Serial.print(bottom);
  Serial.print(" Left: "); Serial.print(left);
  Serial.print(" Right: "); Serial.println(right);
  // Adjust the position based on sensor readings
  adjustPosition(top, bottom, left, right);
  // Small delay to prevent rapid movements
  delay(100);
}

```

3.2.1. Circuit Diagram

The circuit diagram (Figure 7a) of the floating curved concentrator solar system was constructed using Arduino. The LDR module, H-bridge drive, linear actuator and DC motor were integrated with Arduino Uno. Figure 7b illustrates the circuit diagram of the solar monitoring system for this project. This circuit is powered by a NodeMCU (ESP8266) board, a 16×2 bi-colour (red/green) LCD and a mobile application. This system enables the monitoring and recording of voltage, temperature and humidity.

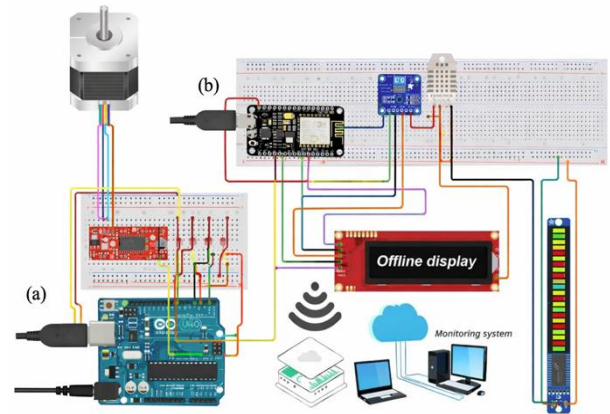


Fig. 7. Circuit diagram of the floating curved solar platform: (a) sun tracking system, and (b) voltage, temperature and humidity recorded by offline and online monitoring systems.

3.2.2.3D Design

The 3D models in Figures 8a and 8b depict the fundamental principles governing the operational mechanisms of the floating platform and its components. The primary role of inverters is to convert the DC output from PV modules into AC. In small-scale, near-shore floating solar PV facilities, inverters can be located on adjacent land. A floating platform and mooring system are indispensable elements of any floating PV installation.

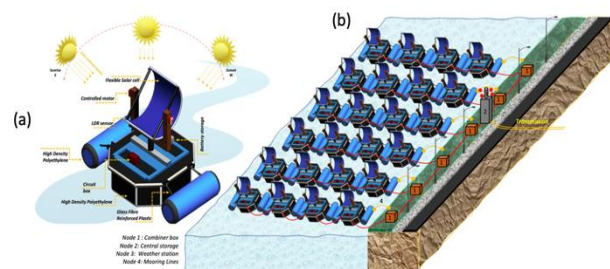


Fig. 8. (a) 3D model of the floating solar platform, and (b) critical components of large-scale floating solar platform systems.

3.2.3. Study Site

Figure 9 presents the data obtained for the selected sites. The Damansara River is a river in Selangor, Malaysia whose catchment is adjacent to Kampung Baru Subang in Selangor. The study site is located at 3°8'45.6" N and 101°32'27.24" E. The Damansara River runs for 22.22 km from Sungai Buloh to Shah Alam. Figure 10 shows how Google

Maps and satellite imagery were used together to accurately delineate the boundaries of the study area. The overall extent of the Damansara River catchment was estimated to cover approximately 116.9 km² [64]. The site environmental conditions during the test day on March 10, 2025 from 12:00 PM to 1:00 PM are 35–39 °C, 11–9 km/h and 62–94%.

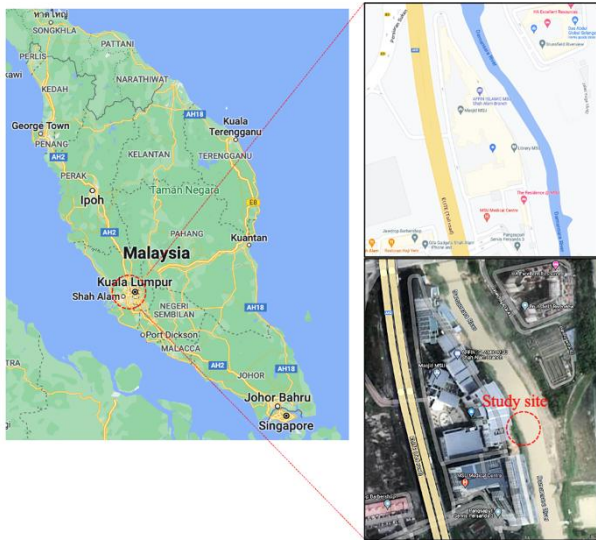


Fig. 10. Map of Malaysia indicating the Damansara River as a study site.

3.2.4. Experimental Setup

The experimental setup of the proposed prototype used an 18 V, 250 W monocrystalline flexible solar panel whose characteristics are listed in Table 2. Data on wind speed were collected from a meteorological weather station located on the riverbank.

Table 2, Electrical characteristics of the monocrystalline flexible solar panel.

Characteristics	Values
Maximum power (Pmax)	250W±10
Maximum power voltage (Vmp)	18 V
Maximum power current (Imp)	13.89 A
Open-circuit voltage (Voc)	21.6 V
Maximum system voltage	DC 600 V
Nominal operating cell temperature (NOCT)	-45 °C to 80 °C
Weight	2.5 kg
Dimensions	(1200 × 800 × 4) mm ³

Figure 9a shows the floating pontoon used in the project. A pontoon is a buoyant system that can hold heavy loads on its own. The platform was built in

order for a series of modules to be arranged in either parallel or sequential order depending on the present needs and available space. Hollow plastic floats were carefully placed together to create a large pontoon with the best buoyancy-to-weight ratio. These floats were made of HDPE, which is known for its high tensile strength, resistance to UV rays and corrosion and low maintenance.



Fig. 9. (a) Floating pontoon, (b) curved trough collector and (c) single-axis tracking system.

As shown in Figure 9b, the prototype used a curved trough solar collector. A linear curved concentrator, a linear tubular receiver and a metal support system make up a traditional parabolic trough concentrator (PTC). A PTC usually tracks the sun using a single-axis system, thereby ensuring that the aperture of the collector is always aligned to capture the most solar energy. The PTC axis usually points north to south and follows the sun from east to west. This technology gathers the largest amount of solar energy during summer when the sun’s rays are at their strongest. Figure 9c shows the one-axis tracking system.

The performance and efficiency of flat PVs can be evaluated in consideration of their electrical power output (PPV) and electrical efficiency (η_{PV}) as defined in Equations 1 and 2:

$$PPV = V_{max} \times I_{max} \quad \dots(1)$$

$$\eta_{PV} = P_{FPV} / (G \times A_s) \quad \dots(2)$$

where V_{max} and I_{max} represent the highest voltage and current that PV modules can produce, respectively, A_s corresponds to the curved surface area of the module and G represents the solar radiation intensity as measured using a UNI-T UT383 illuminance metre with a 5% accuracy. However, for curved surfaces, the enhanced power of PPV was measured using Equation 3:

$$PPPV = \eta_{PPV} \times A \times C \times G \quad \dots(3)$$

where C is the concentrated radius that represents the ratio of the parabola's focal length to the curve's radius of the flexible PV solar panel. Based on the proposed curvature of the solar panel, C takes a value of 1.5. The thermal losses and their effects on the efficiency of floated and flat solar panels can be calculated using Equation 4 [65, 66]:

$$\eta_{PPV} = \eta_0 \times (1 - \beta(T - T_{ref})) \quad \dots(4)$$

where η_0 , β and T represent the initial efficiency at the reference temperature, the temperature coefficient of the solar panel and the actual panel temperature, respectively. The value of β is typically negative, indicating a decrease in efficiency at high temperatures [67], which is equivalent to Equation 5:

$$\beta = 0.04 \times P_{max} \quad \dots(5)$$

4. Results and Discussion

4.1. Final Prototype Configuration

The modular design could support the stable operation of the proposed floating solar platform on the Damansara River by incorporating a curved PV collector, a single-axis tracking mechanism and a buoyant structure. However, the curved solar surface, which is mounted above the floating base as shown in Fig. 11a, may suggest that the significant design concentrates incident solar radiation onto an 18 V, 250 W monocrystalline flexible panel. The tracking system continuously adjusts its orientation to follow the sun. The key design elements also confirm that the integration appears sustained for effective operation. The support from the modular pontoon also ensures effective solar collection. In light of these results, the integrated monitoring system in Figure 11b can

record voltage, temperature and humidity in real time, and these data are transmitted to a mobile application via a NodeMCU ESP8266 module. Both visualisation and storage are well-supported by this configuration. The significant evidence also points to the sustained real-time operation of this system, which links its data to a mobile application for visualisation.

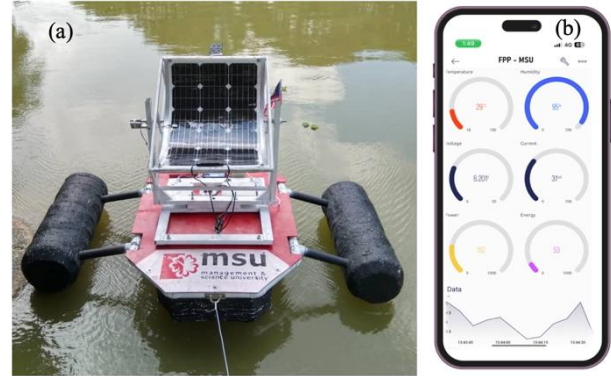


Fig. 11. (a) Final design of the floating solar platform, and (b) a mobile application for solar monitoring at random times.

4.2. Experimental Setup and Environmental Conditions

The performance evaluation was conducted at the Damansara River site in Selangor, Malaysia. The comparative tests between the floating curved configuration and the land-based flat configuration were conducted on 10 March 2025 from 12:00 PM to 1:00 PM under ambient temperatures ranging from 35–39 °C, wind speeds from 9–11 km/h, and relative humidity between 62–94%. In both configurations, electrical power, panel temperature, and ambient humidity were recorded at regular intervals, and solar irradiance was measured with a UNI-T UT383 meter to enable efficiency calculations.

4.3. Power Output Comparison: Floating Curved vs. Land-Based Flat PV

As shown in Figure 12a, the power profiles of the floating curved and land-based flat PV systems reveal important differences in their output. The floating curved setup has a maximum power output of about 231±5 W, whilst the flat land-based setup has a maximum power output of about 190±7 W under the same irradiance conditions. In addition, at a solar radiation intensity of 1200 W/m², the floating curved system achieves an approximately 21% greater electrical efficiency compared with the flat-panel setup at 1200 W/m².

4.4. Temperature and Humidity Behaviour

Figure 12b shows the temperature changes in both systems during the test period. The floating curved panel worked between 27 °C and 39 °C, whilst the land-based panel worked between 25 °C and 37 °C. Even though the peak ambient temperatures were slightly higher at the river site, the floating configuration kept the operating temperatures within a range that allowed the surrounding water body to cool the system effectively. Figure 12c shows that the relative humidity for the floating system ranged from 72% to 90%, whilst the relative humidity for the land-based system ranged from 61% to 75%.

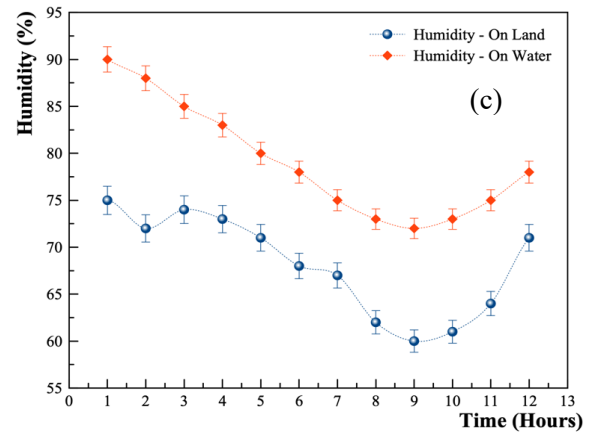
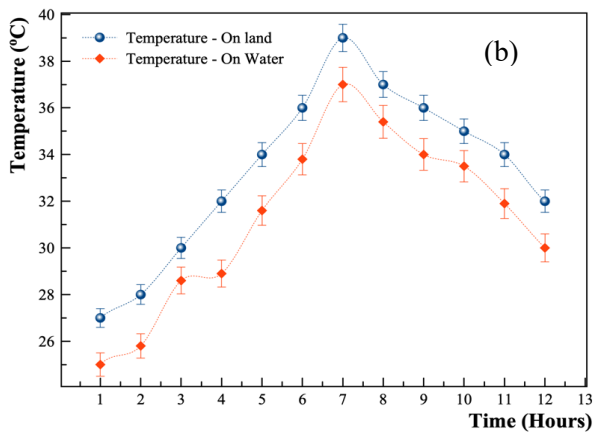
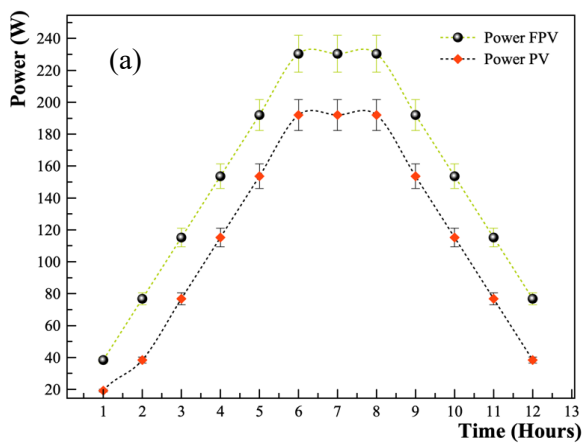


Fig. 12. Readings of (a) generated voltage, (b) temperature and (c) humidity. The test was conducted from 6 AM to 5 PM.

4.5. Efficiency Degradation with Ambient Temperature

Figure 13 shows how the ambient temperature affects the efficiency of both floating and land-based configurations. As the temperature increased, both systems became less efficient at using electricity. However, the floating curved system experienced a much slower efficiency loss compared with the land-based flat system. This behaviour is consistent with the combined effects of water cooling and local humidity, which reduce thermally driven losses and improve the performance of the floating configuration in tropical conditions.

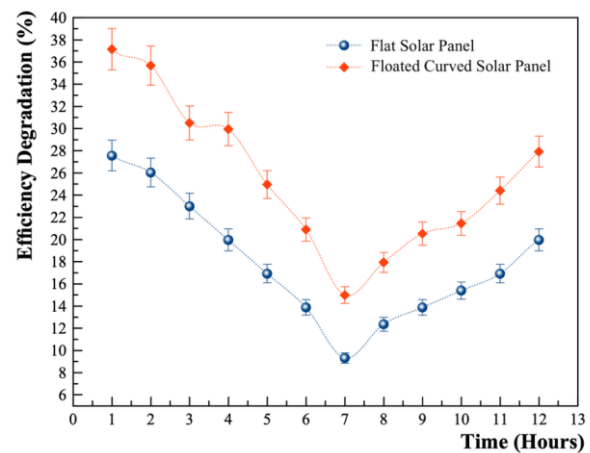


Fig. 13. Relationship between ambient temperature and efficiency degradation.

5. Discussion

The experimental results suggest that the use of curved collectors and single-axis tracking on a floating platform could significantly improve the performance of solar PV systems under tropical river conditions. The floating curved system achieved efficiency gains of approximately 21% over the land-based flat configuration at 1200 W/m². These gains exceed the typical 3%–10% gains observed in conventional liquid solar systems. The cooling and albedo effects alone could not account for these results. Combining optical concentrators with water-induced cooling highlights the feasibility of synergistic increases in energy capture rather than a simple additive improvement over land-based installations. These results also show that the proposed system works on a rotating, robotic setup on the river. Notwithstanding the complexity of these installations, floating solar panels could operate at much lower temperatures compared with ground-mounted panels. These findings support the contention that water-induced cooling can provide additional thermal advantage that is critical to sustained performance gains.

6. Conclusion

This research developed and deployed a floating solar platform that integrates a curved PV solar collector, a single-axis solar tracking system and an IoT-based monitoring system for use on rivers. This prototype comprises an 18 V, 250 W monocrystalline flexible solar panel mounted on a floating pontoon structure and uses Arduino-based tracking and NodeMCU-based data acquisition to measure voltage, temperature and humidity in real time. Comparisons of this floating configuration with a flat solar array installed on land revealed that the former has a maximum power of 231±5 W, whilst the latter has a maximum power of only 190±7 W. In other words, the floating configuration is approximately 21% more efficient than the flat configuration at 1200 W/m² and experiences less efficiency losses at higher temperatures. Using flux concentration, active tracking and water-induced cooling together can significantly improve the performance of PV systems whilst protecting valuable land resources in tropical areas.

Further studies will extend this research through long-term monitoring initiatives across different seasons and river or reservoir locations to test the durability, structural integrity and performance stability of the proposed system across fluctuating

hydrological and climatic conditions. Further research will also examine how environmental factors affect aquatic ecosystems and water quality. An in-depth techno-economic analysis will also be conducted to confirm if larger capacities are cost effective and scalable.

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Credit Authorship Contribution Statement

Safaa Al-Humairi provided the ideas, designed the prototype, conducted the experiments, recorded the data and wrote the first draft. Erold Joel Baeren performed the analysis and investigation.

Data Availability Statement

The data and materials used to support this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

Consent to participate: The authors declared their consent to participate.

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Ethical approval: Not applicable.

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تصميم (شمسي) عائم ومنحني مزود بنظام مراقبة الطقس المعتمد على إنترنت الأشياء للبيئات النهرية والبحيرات

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المستخلص

مكّن الأنظمة الكهروضوئية العائمة من توليد الطاقة الشمسية على المسطحات المائية، مما يخفف من مشكلة ندرة الأراضي، مع توفير فوائد محتملة مثل التبريد وانعكاس الضوء، والتي تسهم في تحسين أداء الألواح الشمسية. ومع ذلك، فإن العديد من الأنظمة العائمة الحالية تستخدم وحدات كهروضوئية مسطحة دون تركيز بصري أو أنظمة تتبع مدمجة، مما يحد من إنتاجيتها الطاقية، خاصة في البيئات الاستوائية مثل الأنهار والبحيرات. تقدّم هذه الدراسة منصة شمسية عائمة تعتمد على تصميم كهروضوئي منحني مثبت على هيكل عائم، بالإضافة إلى نظام تتبع شمسي أحادي المحور، ونظام مراقبة يعتمد على إنترنت الأشياء لمتابعة الظروف الجوية والأداء، ومصمم خصيصًا للتطبيقات النهرية. يعتمد النموذج الأولي على لوح شمسي مرن أحادي البلورة بجهد 18 فولت وقدرة 250 واط، مُشكّل على هيئة منحني (قوسي)، ويتم التحكم فيه بواسطة نظام تتبع قائم على Arduino، إلى جانب نظام مراقبة مبني على NodeMCU يقوم بتسجيل الجهد ودرجة الحرارة والرطوبة عبر تطبيق على الهاتف المحمول. أظهرت الاختبارات العملية على نهر Damansara أن النظام العائم المنحني يحقق قدرة خرج قصوى تبلغ 5±231 واط، مقارنة بـ 7±190 واط للنظام المسطح المثبت على اليابسة، وهو ما يعادل تحسناً في الكفاءة بنسبة تقارب 21٪ عند شدة إشعاع شمسي تبلغ 1200 واط/م². كما أظهر النظام العائم انخفاضاً في تدهور الكفاءة مع ارتفاع درجة الحرارة المحيطة، ويُعزى ذلك إلى تأثير التبريد الناتج عن الماء وارتفاع الرطوبة، مما يقلل من الخسائر الحرارية في الأداء. تشير هذه النتائج إلى أن المنصة الشمسية العائمة والمنحنية المقترحة تمثل حلاً عملياً وصديقاً للبيئة لزيادة إنتاج الطاقة الكهروضوئية، مع الحفاظ على الموارد الأرضية، خاصة في المناطق الاستوائية.